

A flavour physics scenario for the 750 GeV diphoton anomaly

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A simple variant of a realistic flavour symmetry scheme for fermion masses and mixings provides a possible interpretation of the diphoton anomaly as an electroweak singlet “flavon”. The existence of TeV scale vector-like T-quarks required to provide adequate values for CKM parameters can also naturally account for the diphoton anomaly. Correlations between V_{ub} and V_{cb} with the vector-like T-quark mass can be predicted. Should the diphoton anomaly survive in a future Run, our proposed interpretation can also be tested in upcoming B and LHC studies.

The ATLAS [1] and CMS [2] collaborations have presented first results obtained from proton collisions at the LHC with 13 TeV center-of-mass energy. The ATLAS collaboration sees a bump in the invariant mass distribution of diphoton events at 750 GeV, with a 3.9 sigma significance, while CMS sees a 2.6 sigma excess at roughly the same value. Taking these hints at face value, we suggest a possible theoretical framework to interpret these findings. We propose that the new particle is a $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ singlet scalar boson carrying a flavour quantum number. Our proposed framework accounts for three important aspects of the flavor puzzle:

- the observed value of the Cabbibo angle arises mainly from the down-type quark sector through the Gatto-Sartori-Tonin relation [3];
- the observed pattern of neutrino oscillations [4] is reproduced in a restricted parameter range [5];
- the observed values of the “down-type” fermions is well-described by the generalized b-tau unification formula [5–8]

$$\frac{m_\tau}{\sqrt{m_e m_\mu}} \approx \frac{m_b}{\sqrt{m_s m_d}}, \quad (1)$$

predicted by the flavour symmetry of the model.

There are in principle several possible realizations of the 750 GeV anomaly as a flavon [9, 10] : a flavor-carrying $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ singlet scalar. Our main idea is to obtain a scheme where the CERN anomaly may be probed also in the flavor sector. For this purpose we

consider a simple variant of that proposed in [5] in order to address the points above. Phenomenological consistency of the model requires the presence of vector-like fermions in order to account for the observations in the quark sector. Their presence can naturally account for a production cross section of the scalar anomaly through gluon-gluon fusion similar to that indicated by ATLAS and CMS [5] ¹

Here we investigate the allowed parameter space of our scheme which provides an adequate joint description of CKM physics describing the B sector and the recent CERN diphoton data, illustrating how the two aspects are inter-related in our scheme. For definiteness and simplicity, here we focus on a nonsupersymmetric version of the model discussed in [5]. The charge assignments for the fields is as shown in Table I

Fields	L	E^c	Q	U^c	D^c	H^u	H^d	T	T^c	σ	σ'	ξ
$SU(2)_L$	2	1	2	1	1	2	2	1	1	1	1	1
A_4	3	3	3	3	3	3	3	1	1	3	3	1
Z_4	1	1	1	1	1	1	1	ω	ω^2	ω^3	ω^2	ω

Table I. Matter content of the model, where $\omega^4 = 1$.

Here, T, T^c are a pair of vector like “quarks” transforming as $(3, 1, 4/3)$ and $(\bar{3}, 1, -4/3)$ under the Standard Model gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. The scalars σ, σ' are singlets under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ but transform as A_4 triplets and carry Z_4 charge. The scalar ξ is also a singlet under Standard Model as well as under the A_4 symmetry but transforms as ω under the Z_4 symmetry. In addition to the above charges, the scalars and fermions also carry an additional Z_2 charge such that

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¹ Indeed vector-like fermions have been suggested to account for the diphoton anomaly. For an extensive reference set see [11].

the scalar H^u only couples to the up-type quarks, while H^d only couples to the down-type quarks and charged leptons (this Z_2 symmetry would not be needed if supersymmetry were assumed). The invariant Yukawa Lagrangian of the model is given by,

$$\mathcal{L}_f = y_{ijk}^u Q_i H_j^u U_k^c + y_{ijk}^d Q_i H_j^d D_k^c + y_{ijk}^l L_i H_j^d E_k^c + X' T U_i^c \sigma_i + \frac{Y'}{\Lambda} Q_i (H^u \cdot \sigma')_i T^c + y_T T T^c \xi \quad (2)$$

where we take all couplings y_T , y_{ijk}^a and X , Y as real for simplicity; $a = u, d, l$ and $i, j, k = 1, 2, 3$.

Following Ref. [5] after electroweak symmetry breaking and requiring certain hierarchy in the flavon vevs, $\langle H^{u,d} \rangle = (v^{u,d}, \varepsilon_1^{u,d}, \varepsilon_2^{u,d})$ where $\varepsilon_{1,2}^u \ll v^u$ and $\varepsilon_{1,2}^d \ll v^d$, one gets the mass relation between the down-type quarks and charged leptons given by Eq. (1). The up-type quark sector gets modified due to the presence of vector like quarks so that the full up-type quark mass matrix is 4×4 and given by

$$M_u = \begin{pmatrix} 0 & a^u \alpha^u & b^u & Y'_1 \\ b^u \alpha^u & 0 & a^u r^u & Y'_2 \\ a^u & b^u r^u & 0 & Y'_3 \\ X'_1 & X'_2 & X'_3 & M'_T \end{pmatrix} \quad (3)$$

where $a^u = y_1^u \varepsilon_1^u$, $b^u = y_2^u \varepsilon_1^u$; $y_{1,2}^u$ being the only two possible Yukawa couplings arising from the A_4 -tensor in Eq. (2). Also, $r^u = v^u / \varepsilon_1^u$ and $\alpha^u = \varepsilon_2^u / \varepsilon_1^u$. Moreover, $X'_i = X' \langle \sigma_i \rangle$, $Y'_i = Y' \langle (H^u \cdot \sigma')_i \rangle / \Lambda$ and $M'_T = y_T \langle \xi \rangle$. The mass matrix in Eq. 3 is the same as that obtained in [5] where the detailed treatment of the Yukawa sector is given. Notice that the addition of vector quarks only changes the up sector mass matrix, the down sector mass matrix remaining unchanged and thus the relation in Eq. (1) remains unchanged, see [5] for further details.

The scalar sector of the model consists of $SU(2)_L$ doublet scalars H^u, H^d both transforming as triplets under the A_4 symmetry. In addition it contains three types of $SU(2)_L$ singlet scalars with $\sigma, \sigma' \sim 3$ under A_4 while $\xi \sim 1$ under the A_4 symmetry. In order to illustrate how our candidate scalar can account for the 750 GeV di-photon excess, we consider a simplified scenario. Neglecting the mixing between the $SU(2)_L$ doublet and singlet scalars $s^0 = (\xi^0, \sigma^0, \sigma'^0)$ we can phenomenologically express the various scalar mass eigenstates as follows

$$h_i = \mathcal{U}_{ij} H_j^0, \quad (i, j = 1, \dots, 6) \\ \chi_m = \mathcal{O}_{mn} s_n^0, \quad (m, n = 1, \dots, 7) \quad (4)$$

Under this approximation the singlet scalars χ_i can be further decomposed as

$$\zeta \equiv \chi_1 = \mathcal{O}_{11} \xi^0 + \mathcal{O}_{1n} s_n^0, \\ \chi_m = \mathcal{O}_{mn} s_n^0, \quad (5)$$

with $m, n = 2, \dots, 7$ and we have identified the flavon field mass eigenstate ζ as our 750 GeV resonance candidate. Then, this flavon field is composed predominantly

of $SU(2)_L$ singlet scalars. Note that the rotation matrix \mathcal{O} determines the mixing amongst the singlet scalars that form the two A_4 -triplets and the A_4 -singlet ξ .

At the LHC ζ will be predominately produced through gluon-gluon fusion via a triangle loop involving the vector like T-quarks. In the absence of mixing between the $SU(2)_L$ doublet and singlet scalars the tree level coupling of ζ to W, Z bosons can be neglected. Similarly, the coupling of ζ to down-type fermions is also negligible. However the coupling of ζ to up-type quarks is determined by the off-diagonal elements of Eq. (3). Thus, ζ predominantly couples to the vector-like quarks T, T^c . As we show below, the flavour constraints require the vector-like quarks to be quite heavy so that, for a large range of parameters we have $m_T > m_\zeta/2$. Thus, the decay of ζ to T, T^c is also kinematically forbidden.

Therefore, ζ predominantly decays to photons and gluons through the triangle loop involving T, T^c , as shown in Fig. (1) and to up-type quarks through tree-level mixing.

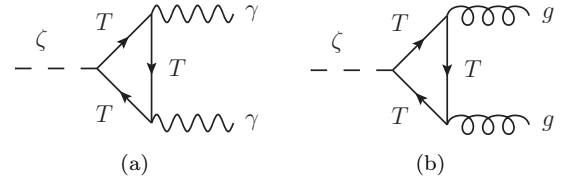


Figure 1. Decays of the 750 GeV scalar to gluons and photons.

Apart from the above channels, ζ can also decay to $Z\gamma$ and ZZ through analogous triangle loops involving T, T^c . Since $m_Z^2 \ll m_\zeta^2$ the decay widths to $\gamma\gamma$, $Z\gamma$ and ZZ channels are proportional to each other, so that,

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{\gamma\gamma}} \approx 2 \tan^2 \theta_W \quad \text{and} \quad \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} \approx \tan^4 \theta_W \quad (6)$$

where θ_W is the weak mixing angle. In general ζ can also decay to two Higgs scalars as we discuss below.

Thus ζ seems, indeed, an ideal candidate to explain the 750 GeV di-photon excess recently observed at the LHC. Both g and γ couple to T, T^c through gauge interactions with interaction strength proportional to α_s, α , the strong and electromagnetic coupling constants respectively. One can write down the effective Lagrangian for the coupling of ζ with gluons, Z boson and photons which is

$$\mathcal{L}_{\text{eff}} = \frac{c_\gamma}{4} \zeta F^{\mu\nu} F_{\mu\nu} + \frac{c_g}{4} \zeta G^{\mu\nu} G_{\mu\nu} + \frac{c_{Z\gamma}}{2} \zeta F^{\mu\nu} Z_{\mu\nu} \\ + \frac{c_{ZZ}}{4} \zeta Z^{\mu\nu} Z_{\mu\nu} \quad (7)$$

where $F^{\mu\nu}, G^{\mu\nu}$ are the usual electromagnetic and colour field strength tensors and $Z_{\mu\nu}$ is the field strength tensor for the Z boson.

In Fig. 2 we show the allowed ranges for the effective couplings required to account for the 750 GeV di-photon

excess for both the CMS and ATLAS experiments within 95% confidence level. In the 8 TeV run neither ATLAS nor CMS have seen any statistically significant excess in any of the $\gamma\gamma$, $Z\gamma$ and ZZ channels. The constraints from 8 TeV run on production times branching fraction $\sigma \times Br(\zeta \rightarrow ff)$; $f = g, Z, \gamma$ for these decay channels can be obtained from [12–15]. In Fig. 2, we have also included the constraints from the non-observation of any signal excess in the $\gamma\gamma$, $Z\gamma$ and ZZ in the 8 TeV run. The upper colored region is consistent only with ATLAS data, while the lower one is consistent with only CMS data, while the middle region is consistent with both CMS and ATLAS. The solid and dashed lines delimit the regions disallowed by 8 TeV data for $\zeta \rightarrow \gamma\gamma$ decay and $\zeta \rightarrow Z\gamma$ decay, respectively. The constraints from $\zeta \rightarrow gg$ as well as $\zeta \rightarrow ZZ$ decays are rather weak and are not shown in the graph. The value of the effective couplings c_γ and c_g are determined by only two parameters, namely the mass m_T of the vector quarks and the strength of the Yukawa coupling ζTT^c . The allowed parameter ranges for the mass m_T and Yukawa coupling y_T for both CMS and ATLAS experiments as well as the constraints from the 8 TeV run are shown in Fig. 3. In plotting Fig. 3 we have required that all the Yukawa couplings remain perturbative over the entire range of parameter space. The color scheme of Fig. 3 is the same as that of Fig. 2.

As shown in Fig. 3, the decay $\zeta \rightarrow \gamma\gamma$ in our model can explain the diphoton excess observed by both CMS and ATLAS experiments. Although the non-observation of similar diphoton excess in the 8 TeV run puts severe constraints on the allowed parameter range, our model still has enough freedom to reconcile these restrictions with the observed 13 TeV excess.

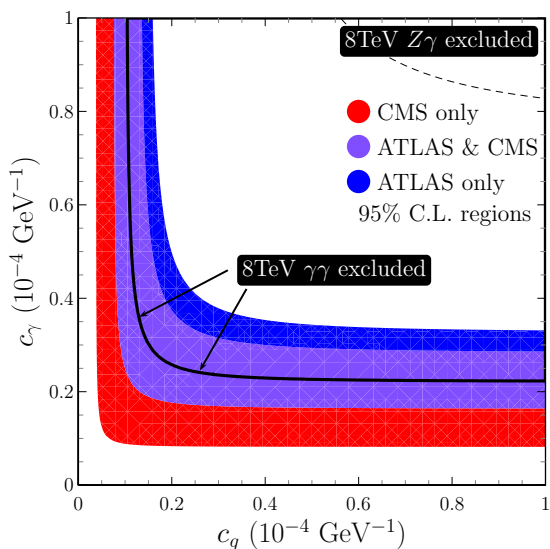


Figure 2. Ranges of effective couplings c_γ and c_g required to explain the diphoton excess at 95% confidence level. Also shown are the regions excluded by 8 TeV data.

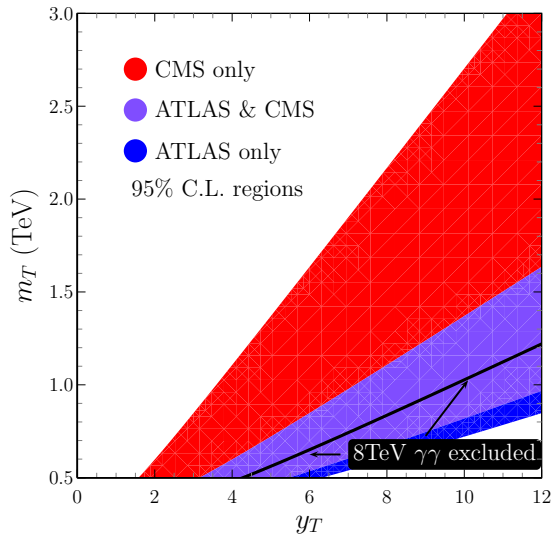
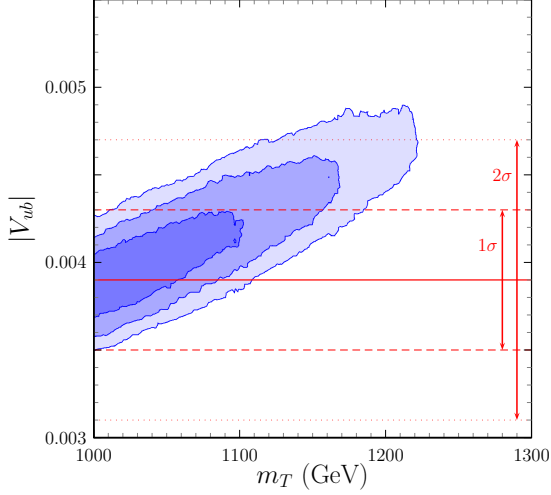


Figure 3. Required vector-like quark mass m_T and Yukawa coupling y_T to explain the 750 GeV excess. Also seen are the regions excluded by 8 TeV data.

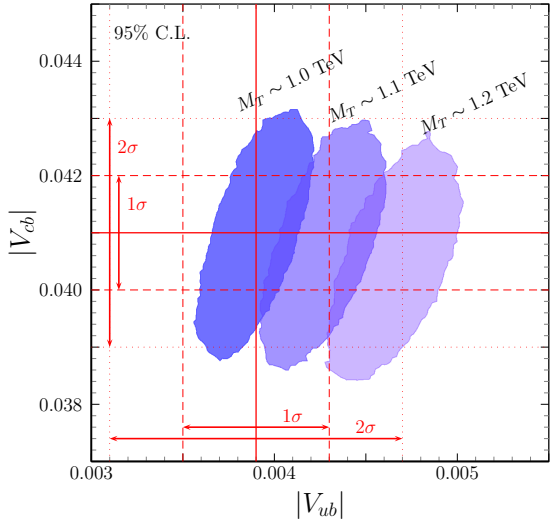
A key feature of our proposal is the identification of the 750 GeV anomaly as a flavon, i.e. a scalar state that carries flavour information. Indeed, our scalar ζ is directly coupled to the quarks, and hence to flavour, so we expect potential correlations between CKM physics and the properties of the observed anomaly. Therefore, in addition to the the quark and lepton masses, related by Eq. (1), the measured neutrino oscillation parameters [4], there are restrictions on the model parameters that come from the consistency of the quark sector, such as the measured quark mixing parameters [16]. In order to explore these implications of the model, one must check, as in Ref. [5] or other generic vector-like scenarios [17, 18], that ours can indeed adequately reproduce CKM physics. To do this we include a selected set of additional observables sensitive to the new vector-like quark T and to the deviations of the CKM matrix from the standard 3×3 unitary form. In particular, we include:

1. neutral meson mixing constraints: in $B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$ systems, mass differences and “golden” CP asymmetries in $B_d \rightarrow J/\Psi K_S$, $B_s \rightarrow J/\Psi \Phi$ decays, bounds on the short distance contribution to the mass difference in the $D^0 - \bar{D}^0$ system, and indirect and direct CP violation parameters ϵ_K and ϵ'/ϵ_K for the $K^0 - \bar{K}^0$ system;
2. rare decays induced by different quark level transitions: $B_s \rightarrow \mu^+\mu^-$, $B_d \rightarrow \mu^+\mu^-$, $B \rightarrow X_s\gamma$, $K_L \rightarrow \pi^0\nu\bar{\nu}$, $K^+ \rightarrow \pi^+\nu\bar{\nu}$, and short distance contributions to $D^0 \rightarrow \mu^+\mu^-$ and $K_L \rightarrow \mu^+\mu^-$.

Furthermore, to reflect LHC bounds on direct production of the new vector-like quark, we restrict our analysis to values of the mass $m_T > 1$ TeV [19]. Once compliance



(a) $|V_{ub}|$ vs. m_T ; 68%, 95% and 99% C.L. regions (darker to lighter) are represented.

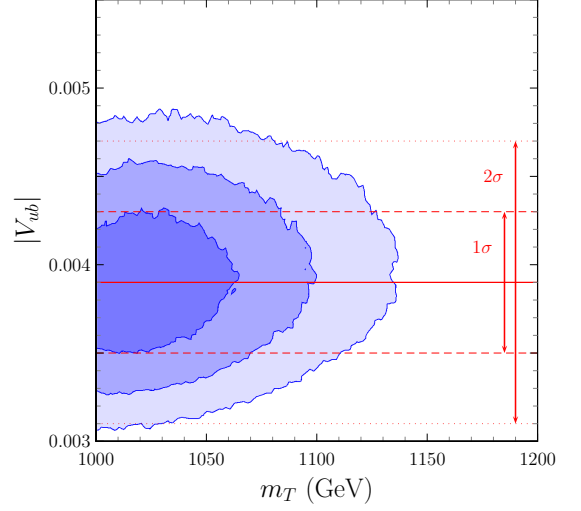


(b) $|V_{cb}|$ vs. $|V_{ub}|$

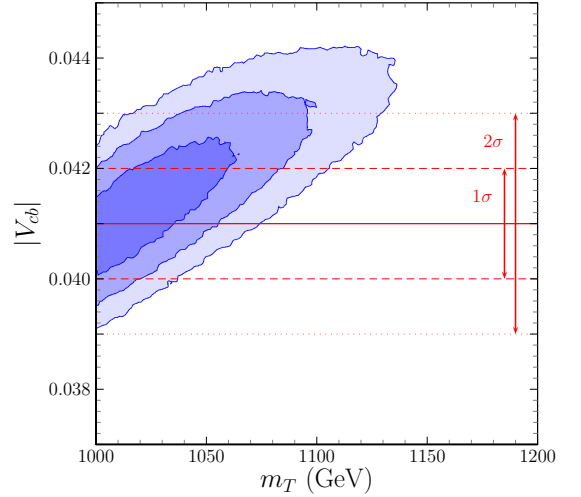
Figure 4. Scenario (A), free $\{X_2, Y_3, M_{44}\}$; experimental central values and 1σ , 2σ intervals are shown for $|V_{ub}|$ and $|V_{cb}|$.

with this set of constraints is ensured, we can address, in addition to the 750 GeV diphoton hint, other features of the model, in particular flavour related ones, like correlations among different observables. Due to the complexity of the problem in terms of the number of independent parameters, we focus on scenarios where the upper 3×3 block of the M_u mass matrix and the remaining mass matrices are fixed, while the X_i , Y_i and M_{44} entries, related to the new vector-like quark, are free to vary. Furthermore, we consider separate variations of : (A) only the largest entries, namely $\{X_2, Y_3, M_{44}\}$, or (B) only (all) the X_i entries.

To cover the available parameter space while maintaining agreement with all of the above constraints, we con-



(a) $|V_{ub}|$ vs. m_T



(b) $|V_{cb}|$ vs. m_T

Figure 5. Scenario (B), free X_i ; 68%, 95% and 99% C.L. regions (darker to lighter) are represented; experimental central values and 1σ , 2σ intervals are shown for $|V_{ub}|$ and $|V_{cb}|$.

duct a likelihood analysis based on Markov chain driven MonteCarlo simulations. Figures 4 and 5 illustrate the results of such analyses. In Fig. 4(a), the correlation among the values of $|V_{ub}|$ and the mass of the new quark m_T is shown for scenario (A): in that case, accommodating larger m_T values comes at the price of increasingly larger values of $|V_{ub}|$. To further illustrate the situation, Fig. 4(b) displays the correlation among $|V_{ub}|$ and $|V_{cb}|$ for separate ranges of m_T values, $m_T \in [1.00; 1.02]$ TeV, $m_T \in [1.10; 1.12]$ TeV and $m_T \in [1.20; 1.22]$ TeV. In addition to the features seen in Fig. 4(a), Fig. 4(b) shows an additional (milder) correlation among $|V_{cb}|$ and m_T : larger masses prefer smaller $|V_{cb}|$ values. Figure 5 corresponds instead to scenario (B). In this case the corre-

lation trends are reversed with respect to scenario (A): while $|V_{ub}|$ is almost uncorrelated with m_T , $|V_{cb}|$ tends to be larger for increasing T-masses. It is also to be noticed that the range of m_T values is much more limited than in scenario (A).

Finally, we briefly comment on the issue of width of the 750 GeV resonance. The first thing to notice is that with the current low statistics, the estimates for the decay width are very poor. This is reflected in the fact that, while the ATLAS experiment prefers a broad decay width of around 45 GeV, the CMS data suggest a decay width of few GeV. Such uncertain decay width estimates are likely to change significantly in the next run, if the anomaly survives.

In our model, since the $\zeta \rightarrow TT$ decay is not kinematically allowed, the decay width of ζ is a priori narrow. Even though $\zeta \rightarrow t\bar{t}$ decay is mixing suppressed, it can

contribute to the total width from a few hundred MeVs up to 10 GeVs. Partial widths to lighter fermions are smaller as well as that for the $\zeta \rightarrow hh$ decay (where h is the Standard Model Higgs boson) which is constrained by the LHC Run1 data. If in future runs the ATLAS experiments confirm that a broad resonance persists this would imply that a significant novel decay of ζ is at work.

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